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ABSTRACT

The implementation of basic research on children's scientific thinking into science curricula continues to be a slow process. This chapter summarizes research on cognitive development that has helped to establish the goals for much of early science education and examines its implications. The chapter begins by describing scientific thinking and linking it to a model: (1) understanding the need for explanation, influenced by developmental constraints; (2) understanding that observable data are essential to substantiate claims and are linked to intuitive theories and previous experience; and (3) understanding that explanations need to meet logical criteria and are influenced by teacher practices. The chapter examines research on children's development of an understanding of mental states and activities and application of this understanding to science thinking and discusses research on children's ideas about science. Finally, the chapter considers the teacher's role and examines the types of intervention suggested from various lines of research, including using conversation, documenting children's thinking, using drawing to learn scientific concepts, and incorporating collaborative problem solving. The chapter concludes by noting that the model of science thinking helps to develop a constructivism that accounts for the interchange among children, their peers, and their teacher and that recognizes developmental constraints and the importance of children's intuitive understanding. This perspective leads to a social constructionism that is child-centered while acknowledging the teacher's role in bridging the discovery process and socially constructed symbol systems. (Contains 58 references.) (KB)

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CHAPTER 6

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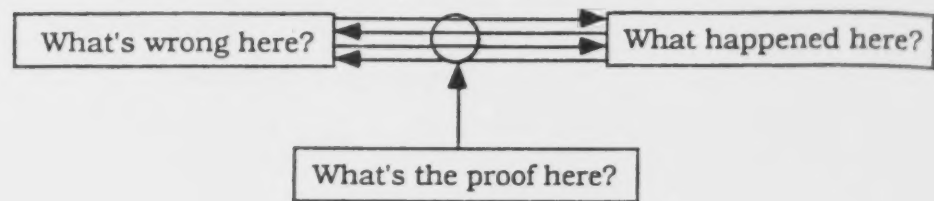
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YOUNG CHILDREN have a natural inclination to learn about their world, and they spend a great deal of time engaged in physical exploration of it. Mealtime alone, as any parent knows, provides seemingly endless opportunities for children to investigate the nature of solids and liquids, changes in temperature, the use of simple tools, and the behavior of objects in motion. Children engaged in such activity are engaged in science—by which we mean the process of developing explanations about how the world works—and are developing useful and quite powerful scientific theories. Such informal science learning, we will show, must be respected and understood as we consider research on the more formal learning of science that takes place in the preschool or kindergarten classroom.

Research on early science education needs to be distinguished from research on early cognitive development. Research on cognitive development helps us understand developmental constraints on learning (such as the ability to recognize anomalous events) as well as the common misconceptions children have about a certain concept (e.g., Levin, Siegler, & Druyan, 1990). Research on science education helps us determine useful procedures to facilitate scientific thinking in young children. Such studies that deal with children under 7 or 8 years of age remain relatively difficult to find. In this chapter we present what we have found in recent journals. As a context for this research, we also summarize the cognitive development research that has helped established the goals for much of early science education.

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Figure 6.1. Diagram of scientific thinking

SCIENTIFIC THINKING

Scientific thinking is a specific application of curiosity and intelligence. This form of thinking consists of the gradual understanding that certain events are anomalous and need to be explained (*What's wrong here?*); that observable data are essential to substantiate one's claims (*What happened?*); and that explanations need to meet certain criteria of logic (*What's the proof here?*). These three orientations to the world occur to children at staggered times of onset, probably in the order mentioned. The orientations can be diagrammed as a set of relations (see Figure 6.1).

The first orientation to the world represents a shift from a passive acceptance of an event to an active comparison of that event with something that was expected but did not occur. For example, the child sees a heavy object float and compares that with her expectation that this heavy object should sink. The child, through her advance to comparative thinking, has asked the first question: *What's wrong here?*

Some children may sense the anomaly but dismiss it as an isolated case. In our example, the child might think: *This* heavy object floats. The child may not relate *What happened?* to a class of events—all heavy objects float in water—but merely to the local case of one object. To proceed further, the child needs to sense that one case has implications for many cases. Furthermore, if this anomalous case is accepted, the expected case (heavy objects sink) has to be reworked.

Thinking traffics between *What's wrong?* and *What happened?* First the child tries an exact replication, just to see if the heavy object floats again (first arrow from left to right in Figure 6.1). On further inspection the child might realize that the object floats but that it pushes a bit into the water before it stabilizes. So the child reflects on the events and reinterprets her definition of *What's wrong?* (first arrow from right to left). Instead of saying, "This heavy object floats when it should sink," the child

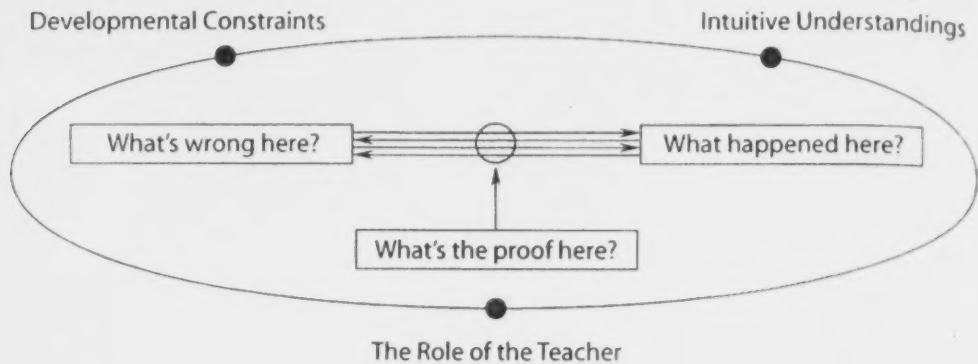
might rephrase what's wrong as "This heavy object sinks a little in the water when it should sink all the way."

This revision in turn might lead to a reworking of what happened, for example, "The object pushes against the water." The child has now moved beyond causing and into testing to see what will happen (second cycle of arrow). She makes certain things happen in order to confirm a prediction. She pushes down on the object to test its strength against her finger. This shift from causing to testing is critical to scientific thinking. This cycle among causing, interpreting, and testing is the foundation for scientific thinking and occurs in preschool-aged children (see Forman & Hill, 1984).

The step toward proof comes more slowly. At the intuitive level, proof consists mainly in making the strange familiar. Children reason by analogy. In the higher levels of science, proofs are accomplished by relating the strange to the familiar via a set of formal procedures (e.g., math) that in turn flow one to another without gaps in logical consistency. For example, the mathematical laws of falling objects, consistently applied, can account as well for the laws of orbiting satellites. For the child, proof begins as a case of analogy and consists of realizing that the event in question is actually similar to a more familiar case. For example, the child might use analogy to progress from "The heavy object is large" to "Large objects are strong; therefore strong objects can hold themselves up in water." But the proof has been inconsistently applied here, because it applies only to heavy objects that float, not to those that sink.

An arrow in Figure 6.1 connects the proof box to the traffic between the upper two boxes. This symbolizes that proof is metacognitive. That is, proof refers to thinking about thinking, in this case, the relation between hypothesis (*What's wrong?*) and facts (*What happened?*). *What's the proof* addresses the issue of how information constrains an answer to the only one possible and does not accept the same answer for opposite events (some sink, some float). As we review recent research later in the chapter, we try to assess where young children are in their understanding of proof.

While this diagram offers a useful representation of children's scientific thinking, it may be helpful to broaden our perspective somewhat and consider factors that research has identified as being critical to successful learning in the classroom. Figure 6.2 places our model in a context that reminds us that science education in school is in part a function of (1) cognitive development issues; (2) children's prior experience with and intuitive theories about science; and (3) the role of the teacher. (We could easily have added two other factors: the role of the *family* in encouraging scientific thinking and the importance of providing a rich learning *environment*—but in the interest of brevity we will focus our attention on the

Figure 6.2. Context of children's scientific thinking

three areas illustrated in Figure 6.2.) The following sections address each of these topics in turn, within the context of recent research.

DEVELOPMENTAL ISSUES: CHILDREN'S CONSTRUCTION OF MIND

The process of doing science requires that the child recognize when an event (this heavy object floats) conflicts with her understanding of how things work. In addition, science involves not only the construction of new knowledge, but also the construction of some means to communicate one's discoveries, to explain and defend one's ideas, and to consider the ideas and theories of others. One may know but not be able to explain. Communication necessarily requires a certain level of metacognitive processing, of stepping back and reflecting on one's own thoughts. In addition, children require a reasonably developed theory of mind before they understand the necessity to explicate their knowledge for others. These issues bring the children's concept of mind into the center of research on science education.

Research on cognition has attempted to determine when children develop an understanding of mental states and activities: belief, desire, memory, inference, and so forth. For those involved in early science education, this research can perhaps shed some light on two aspects of children's science: the child's interpretation of a physical event, and the child's ability to engage in meaningful conversation with others about that event.

Pillow (1988), in a summary of research into children's beliefs about

the mental world, cites several studies showing that young children often miss helpful cues about their own cognitive processes. Six-year-olds, for example, when given instructions that could not possibly be carried out, tried to carry out the instructions instead of realizing that they had failed to comprehend the impossibility. Flavell (1988) found that while 5-year-olds showed nonverbal signs of comprehension problems, such as pauses and puzzled expressions, they did not report an awareness of their own comprehension difficulty when asked. Older children had a higher degree of awareness. Young children may not realize the significance of their fleeting feelings of uncertainty. In other words, their puzzlement does not cause them to reflect on its source.

What happens when we carry these findings over to our model of science thinking? Clearly, it becomes difficult to assume that the young child will necessarily recognize a conflict (*What's wrong here?*) between her existing knowledge structure and a physical event she observes. Cognitive conflict may not occur. If the child, for example, ignores her puzzlement upon seeing a heavy object float, and if this child does not reflect on her own prior conceptions, then the existing knowledge structure will remain unchallenged.

Having briefly dealt with knowledge of mind as it affects the child's interpretation of physical events, we now turn to knowledge of mind as it relates to communication with others. Science, for children as well as adults, is not done in a vacuum but in a social realm within which ideas are discussed, are debated, and take shape. For any meaningful give-and-take to occur, there must be agreement about the facts (*What happened?*) even if there are differences of interpretation. Konicek, King, and Teece (1990) report on the care taken by fourth-graders to distinguish "floating" from "not sinking" objects. But, as Pillow (1988) summarizes, younger children's incomplete understanding of mind often prevents them from taking the perspective of others that useful dialogue requires. Young children do not, for example, understand that a person's prior knowledge or expectations may affect that person's interpretation of a physical event. Pillow offers an example. Children see an object and are then shown an uninformative patch of that same object. Next they are asked whether someone seeing just the patch could identify the object. Most 4- and 5-year-olds incorrectly said "yes." They confused their own privileged information about the whole object with the partial information given to a new viewer. Such a failure to take the other's perspective would make it difficult for a young child to debate alternative views. Nevertheless, these early struggles at communication are the origins of social perspective-taking and collaborative problem solving. By 8 years of age these egocentric errors are rarely made.

What emerges is a picture of the young child only gradually developing an ability to decenter, to be objective enough to fruitfully compare his experience with that of his peers. We might expect that our young learner at water play would be unperturbed by the claim of a peer that a heavy object floated, but eventually perplexed if she discovered this herself. Later, perhaps at age 6 or 7, she will more readily agree with her peers that these facts present alternative views that need to be reconciled. Then she will begin to traffic freely between *What happened?* and *What's wrong?* This does *not* mean, as we show in our section on teaching strategies, that young children cannot engage in science. It does mean that the teacher, aware of these developmental constraints, will want to employ techniques that help children around them.

INTUITIVE UNDERSTANDINGS: CHILDREN'S THEORIES ABOUT SCIENCE

Having reviewed research about children's ability to *do* science—to recognize cognitive conflict and to engage in fruitful discourse with others—we turn now to research on children's ideas *about* science. The early work in this area gave much attention to the developmental level of children. Developmental level refers to general cognitive competence, such as the ability to conserve quantity (same amount despite spatial changes) or the ability to understand class inclusion relations (some is less than all). More recently, research has taken us to specific content, such as the misconceptions children have about heat or gravity or light. In this section, we focus primarily on content-specific research.

Principles of Constructivism

As we discussed earlier, children bring to science instruction a great deal of experience and many ideas about how things work. These ideas have been called naive theories, alternative frameworks, misconceptions, and intuitive understandings. What these terms have in common is the belief that children have constructed, through high-level thinking, their own theories about physical events. The naive theory has a sophistication of its own (see the discussion of Figure 6.1) and has been adopted (and retained) by the child because of its proven explanatory power. Thus, the teacher cannot ignore the naive theory or simply ask the child to abandon it in favor of more orthodox views. The child who is told a new explanation will often concurrently hold the misconception because it is more

integrated into many other assumptions he has developed through experience in the world.

In fact, these early theories are so powerful that honors students studying college physics will fall back on them when asked to apply their knowledge to new situations, and they are widespread even among schoolteachers who teach math and science (Ginns & Watters, 1995). In the classroom, as Gardner (1991) makes clear, students may learn to provide the expected answers when tested in science, but they may never abandon the quite contradictory notions formed in early childhood. Real learning in science, then, must involve a process of conceptual change, not just the accumulation of facts. This process of reconstructing misconceptions, called constructivism, requires reconciling the intuitive theories of the young child with the expert theories developed by scientists.

Constructivism acknowledges several principles—some obvious, some less so. No one seriously assumes that the young child is a blank slate, so it is trivial to cite the *tabula rasa* theory as something constructivism is not. Even empiricism does not assume that 4- and 5-year-olds come to science instruction without preconceptions. But beyond this obvious principle, constructivism also posits that inference, not the raw observation of noticeable events, is the ultimate source of knowledge. Only through inference can the child organize facts into a coherent system. Furthermore, while misconceptions have a coherence that makes them resistant to mere replacement by new information from the teacher (Carey, 1986), constructivism holds, as a principle of faith, that children will be conflicted when anomalies occur and that they have innate capacities to make the inferences necessary to resolve these contradictions (Wheatley, 1991). In a constructivist classroom, teachers do not directly teach these competences but rather establish an environment that allows the children to draw on them (Duckworth, 1996). The teacher's role, which we explore in some detail later in the chapter, becomes less one of imparting information and more one of scaffolding the child's learning by (for example) increasing the likelihood of cognitive conflict, or what Gardner (1991) calls Christopherian encounters: situations in which the child must confront evidence that challenges his intuitive theories' (the term honors Columbus's irrefutable proof that the earth is indeed round).

Before moving from this all-too-brief encapsulation of constructivist theory to its implications for the teacher of young children, we first (1) use evaporation to examine more closely the process of conceptual change, (2) review similar research in other content areas, and (3) discuss recent research that refines, or even challenges, the constructivist model of science education.

Conceptual Change: Evaporation as a Case in Point

In the following example, we consider the formation and development of misconceptions. We show why these misconceptions are more than quaint, but are intuitively reasonable. This is important, because only when a teacher understands why a student's misconception is reasonable does the teacher have an entry point for effective instruction. In the service of this objective, we use one science concept, evaporation, as a case in point so that we might more fully trace the misconceptions children bring to their classwork.

Most of us have seen the surprise in a child's face when the untouched water dish, wet an hour ago, is now dry. This surprise itself comes from a rather elementary theory about liquids: (1) Liquids do not spill up, and (2) liquids do not disappear into thin air. Yet the water is gone, but the dish remains. The observation of the missing water in the presence of the empty dish violates these assumptions and leads to the first stage in Figure 6.1: *What's wrong?* From this point on, children have a variety of explanations about what happened.

Some children will cling to their theory about liquids and consider the nature of the dish. Children in the 7- to 8-year range think that the dish absorbed the water (Bar, 1989). They have some understanding of how water seeps into the ground, or into a sponge, so why not into a dish? This explanation is a first attempt to say *What happened here?* Since the children do not know that water can change from a liquid to a gas (called a phase change in science), they feel compelled to justify the *What's wrong?* question with a reworking of their assumptions about solid containers.

By the age of 9 or 10, children begin to talk about vapor, but it is a transitory concept and situationally applied. They believe that water can turn into vapor, but they still think that this vapor is contained in the clouds but does not constitute clouds (Bar, 1989). The children are comfortable with the idea of vapor because they think vapor is similar to air. They know that air is present but cannot be seen. But since they still think that vapor must be contained by something (the cloud), we can surmise that their understanding of phase change is incomplete. They understand that the water becomes vapor, but that is not the same as understanding that the water is transformed into vapor. To say that water becomes vapor is not much more than saying that water becomes invisible. The children have not tried to account for what it is about vapor that makes it invisible (drops too tiny to see). Vapor is just water that one cannot see; therefore it still has all the other properties of water (e.g.,

existence and weight) and so requires a container if it is to be "held" in the sky.

Figure 6.1 is again helpful in discussing children's construction and reconstruction of theory. The first *What happened?* referred to the absorbent dish; the second *What happened?* referred to the water becoming invisible and residing inside clouds. This progress is usually the result of a reworking of the *What's wrong?* question. Children try to make the dish soak up the water; it doesn't, so the first *What happened?* makes no sense. The children find it unavoidable to construct the idea of water moving because they are not willing to posit the annihilation and re-creation of matter. The theory about water moving comes when they relate the evaporation dish to a pan of boiling water. Vapor is invisible steam. In this way the children do not have to violate their belief about matter. They just add that some matter is invisible!

It is not until age 11 or 12 that children construct a coherent theory that accounts for both the invisibility and movement of water (Bar, 1989). The water vapor is made of drops that are so tiny that they cannot be seen (i.e., "They are scattered everywhere in the air"); and because they are so tiny, they can be moved by the air. Thus the phase change of water into particles accounts for the invisible movement. Likewise the particle theory explains how clouds can be made of vapor rather than containing vapor. For these older children, the proof that water vapor exists comes from their understanding that it *must* exist. Given the constraints that liquid water is heavier than air, and all other constraints, water vapor is a case of logical necessity. Similar findings come from Beveridge (1985), who extended his research to include condensation.

Research About Other Topics

As the constructivist model of conceptual change has gained widespread acceptance, researchers have tried to determine children's misconceptions across a broad range of domains, only a few of which can be reviewed here. The reader interested in more information is referred to existing bibliographies of conceptual change research (Pfundt & Duit, 1994) or, for example, to the research base of the National Curriculum in England (Department of Education and Science, 1989), which includes children's theories about growth, evaporation and condensation, light, change in nonliving materials, sound, electricity, forces, and living things and their environment.

One of the most exhaustive and useful studies of children's theories about living things was conducted by Susan Carey (1985), who investi-

gated the naive theories children (aged 4, 6, and 10 years) have about biology (living versus inanimate; plant versus animal; and the processes of eating, breathing, sleeping, dying, etc.). The younger children explained bodily processes in terms of social and psychological needs. For example, to the question "Why do we eat?" the young child might say, "To grow big and strong." By age 10, an "intuitive biology" emerges, with explanations similar to those of naive adults. Carey's point is that these later theories are qualitatively different from the early theories, even though they both may be incorrect: that children undergo a process of true conceptual change in which old theories are restructured and new ones emerge. This work challenges the accretion model of learning science (Lawson, 1988) that we discuss in the next section. For more work on children's ideas about ecology and matter, see Leach, Driver, Scott, and Wood-Robinson (1996).

Feher (1990) and Rice and Feher (1987) have done careful work on children's understanding of paths of light. By using the inversion of an image through a pinhole, these researchers discovered some intriguing misconceptions about light rays being "squeezed" and then "bulging out" as they pass through holes.

Galili and Bar (1997), who studied the knowledge children (ages 5 to 16) have about weight, found that young children develop their ideas based on tactile experience ("Suspended objects have no weight" is a typical misconception of young children) before becoming conservers of weight. They found that while children modify their knowledge, it was not always a complete substitution of a more advanced theory for a flawed one; depending on the situation, a young child may be both a conserver and a nonconservor.

A few of the other content areas to be studied by researchers in recent years include magnets, environmental knowledge (Palmer, 1996), forests and their inhabitants (Strommen, 1995), the concept of burning (Boudaoude, 1991), dissolving (Longden, Black, & Solomon, 1991), earthquakes, the shape of the earth (Arnold, Sage, & Worrall, 1995), and astronomy (Brewer & Samarapungavan, 1991).

In response to such work, Johnson and Gott (1996) argue that such studies may be unreliable because (1) laboratory tests make it difficult to elicit the real knowledge of children, which is imbedded in personal contexts and meaning; (2) such tests are likely to prompt instant answers instead of ones based on reflective thinking; and (3) children may misinterpret the researcher's question and the researcher may misinterpret the children's response. Chinn and Schaverien (1996) agree that children must develop trust in the researcher before they become willing to articulate shaky or partly formed ideas; their methodology emphasizes the es-

establishment of a close working relationship between researcher and child, as does that of Maria (1997). Both these studies offer useful guidance for the would-be researcher of children's theories and answer the objections of Johnson and Gott (1996).

Constructivism Reconsidered

The orthodoxy of constructivism is gradually being refined. Shapiro (1994) asks the practical question of why some children do not progress, even when placed in rich problem-solving environments that challenge their misconceptions. By using children's understanding of reflected light, she investigated the interaction of science learning and personality type. While this study deals with children 11 years old and older, as a research (and teaching) methodology it is well worth reading. Shapiro found that the social orientation of students contributed to their success or failure. Some children are socially acquiescent; that is, they defer to more dominant children. Others embrace the challenge of negotiating for equal status. While the socially acquiescent child does not profit from the confrontation of ideas, the socially embracing child does. Shapiro presents a needed refinement to the oversimplification that children universally have a fascination with contradiction, and she reminds us that science education involves emotional, social, and cultural issues as well as cognitive ones.

Other researchers have questioned whether conceptual change is the most accurate model of science education. Lawson (1988) interviewed elementary school children (aged 6, 9, and 11 years) to determine the extent to which they held naive misconceptions about biological concepts such as growth, circulation, and family resemblance. He found no evidence of coherent misconceptions, but rather scattered bits and pieces of knowledge (see also diSessa, 1988; Russell, Harlen, & Watt, 1989). If this is true, one would have to reason that didactic teaching could be justified, since the scattered facts would not be resistant to replacement. Lawson (1988) argues that, at least with these concepts, one should adopt an accretion theory of learning rather than a reconstruction theory. An accretion theory holds that knowledge builds in a quantitative manner as more and more facts are learned. A reconstruction theory holds that the learning comes not primarily from the acquisition of new facts, but from a reconfiguration of the system of relations among the facts.

Mintzes (1989) writes a rebuttal of Lawson by reviewing other early childhood research on naive theories of biology (Carey, 1985; Wandersee, Mintzes, & Arnaudin, 1987) but admits that the construction of a well-formed naive theory of biology may take longer than the construction of

a well-formed naive theory about physical objects. He attributes this delay to the relative inaccessibility of observable events necessary to found naive theories of biology. One can also see in the case studies that Lawson (1988) provides that the youngest child was socially acquiescent. Thus the lack of a well-formed theory could be either real or simply not expressed (see Shapiro, 1989).

The possibility remains that (at least with some domains) children younger than 10 years old form loosely held analogies rather than coherent theories. For example, the rain cycle is understood as analogous to "raining up" and "raining down," without the children understanding the necessity for state changes in the water during evaporation and condensation. Does this imply that we should encourage children younger than 10 to forget their wrong analogies and to accept the more useful analogies of the teacher? Russell and colleagues (1989) argue that even if children construct loosely knit systems of attributes, they are still constructing relations; the learning child does more than accrete new facts. Thus, if we tell a child to forget a wrong fact without our understanding his loose system of relations, that wrong fact will very likely be reinvented in some other form to support his loose system of ideas.

Linder (1993) argues that the cognitive change model puts too much emphasis on displacing the child's intuitive theories. Science, he contends, is not about giving up one conception in favor of another, but of knowing when various theories (intuitive versus expert) apply. For example, a physicist using a vacuum cleaner at home might talk of it "sucking up" the dirt, even though he would not use such a framework in the laboratory. In a similar vein, Howe (1996) suggests that we modify constructivist theory by adopting a Vygotskian perspective that is less confrontational than the current model. She writes:

In contrast to the conceptual change model, a model that accepted a Vygotskian view of the development of concepts in science would accept children's ideas as a starting point with a view toward helping them expand their knowledge, learn to use it more flexibly, apply it to more situations and, eventually, to integrate it into a system of broader, more inclusive concepts. (p. 36)

The influence of Vygotsky's sociocultural perspective would lead to a form of constructivism, Howe argues, that would rely more on discourse, allow ample time for children to reflect on and accept new ideas, and shift the focus from the solitary child to cooperative learning within a social context (Howe, 1996).

Elkind (1989), likewise, warns us not to rush 4- and 5-year olds into

performing controlled experiments. Children this young do not possess the cognitive wherewithal to isolate variables or to understand the interaction of two or more causes (see also Rudnitsky & Hunt, 1986). Elkind's warning pertains more to *What's the proof?* in Figure 6.1 than to the wonderful messing about that young children can handle when perplexed by some anomalous event. Science for these young children is quite possible, if by science one means the construction of some expectation, trying something out to confirm that expectation, and modifying the expectation based on observations. This type of science can happen even in the absence of an appeal to proof or logical necessity (concrete operational thinking).

We appreciate the contributions of Linder, Howe, and Elkind as we adapt the basic constructivist approach to the specific needs and abilities of young children. After all, constructivism should not be thought of as a one-size-fits-all framework, but one that is applied in developmentally appropriate ways. Extensive work with young children in the United States (Forman & Hill, 1984) and in Reggio Emilia, Italy (Edwards, Gandini, & Forman, 1993), supports Howe's call for science education that (1) allows adequate time for exploration, investigation, and reflection; (2) is supported by the skillful intervention of the teacher; and (3) is carried out in a respectful social context in which children and teachers become partners in learning.

Driver, Asoko, Leach, Mortimer, and Scott (1994) raise another issue, arguing that the constructivist model of conceptual change ignores the fact that science is not merely about personal discovery based on experience with physical phenomena, but is also a process of enculturation into the symbols and conventions of the scientific community. Science is not only, or even mostly, about learning from nature, but is about learning the social constructs that have been invented to explain natural phenomena. Since no student could possibly discover these constructs on his own, they suggest, it is as inaccurate to suggest that science knowledge is discovered by the learner as to suggest that it is transmitted by the teacher.

Driver and colleagues challenge the overly simplified reduction of constructivism to mere hands-on learning and move us closer to a constructivist theory that accounts for both the process of personal discovery by the learner and the critical role of the teacher in introducing the learner to the tools and symbols of science. Becker and Varelas (1995) help us reach this goal by advocating a Vygotskian model that nicely accounts for the teacher's contributions. Knowledge in the Vygotskian sense is a two-way process in which the child is being empowered as an independent thinker while being inducted into the cultural practices of science (Becker & Varelas, 1995). The teacher's role is to bridge these top-

down and bottom-up processes by scaffolding the child's learning; that is, by offering the socially constructed symbol systems, models, and other tools that the child needs to create his own understanding. Learning, then, is partly a process of personal discovery and partly a process of mastering the use of existing symbol systems. Their model dovetails nicely with the Vygotskian approach proposed by Howe (1996).

In summary, recent research has refined and strengthened our constructivist theory of science learning. We have moved in recent years from a simple conceptual change model, in which the child uses anomalous data to modify his existing theories, to a social constructivism model that better explains the more complicated reality of the child creating personal understanding within a broader context of socially constructed scientific symbols and methods. This revised model helps us account for the crucial role of the teacher and of peers in the learning process, and it helps us adapt the constructivist model to the developmental needs of young children.

THE ROLE OF THE TEACHER: RESEARCH ON TEACHING EARLY SCIENCE

What is an early childhood science teacher to do? The research in this area suggests several forms of intervention, which, at times, includes no direct intervention. Duckworth (1996) makes an eloquent case for allowing students to discover and frame their own questions. The intervention, in this case, consists mainly in providing the children with a rich problem-solving environment and a teacher who reflects and records the evolution of the children's thinking. Wasserman (1988) offers a model described as play-debrief-replay. This model puts heavy emphasis on group discussion and repeated alternations among messing about, summarizing, and a higher level of messing about. As alluded to in our discussion of children's theories of mind, teachers need to monitor the communication competence of children before launching these more routinized formats of instruction.

The conceptual change model would suggest that teachers must introduce data that conflict with children's theories. But Chinn and Schaverien (1996) warn that anomalous data alone may not be enough to cause children to rework their ideas. They describe seven typical responses to conflicting data—only one of which leads to theory change. Chinn and Schaverien suggest that in order for anomalous data to be effective, the teacher must reduce the entrenchment of prior theories.

introduce a plausible alternative theory, make the anomalous data credible, and encourage reflective thinking.

Beveridge (1985) used conflict inducement to study children's theories about the water cycle. Some children were asked to test water absorption using paper towels, a plastic saucer, a sponge, aluminum foil, and a metal plate. The results of these tests were meant to conflict with the students' assumption that evaporated water had been absorbed by the dish. Other children were given a lesson on steam. A mirror was placed in front of a boiling kettle and the condensation was noted.

It is interesting that these demonstrations did little to facilitate reconstruction of naive theories. Beveridge concludes that these demonstrations were ineffective because the alternative theories were resistant to change. While this borders on circular reasoning, we appreciate the intent of that conclusion. The techniques were didactic. Instead of placing the children in a situation in which they would invent their own tests (and therefore their own understanding of what the test tested), the teacher presented the test and demonstration as a given.

In contrast to the method Beveridge tested, the teacher might more profitably introduce into the learning environment materials that increase the likelihood of cognitive surprise. Unexpected events, when imbedded in the child's own process of exploration, provide rich opportunities for encouraging the flow of thinking diagrammed in Figure 6.1 (Forman & Hill, 1984). In the following sections we describe strategies that can help children become aware of their thinking (*What happened?*) and test their ideas (*What's the proof?*).

Conversation

Our model of social constructivism has the child, not the teacher or curriculum, at its center. Therefore, Shapiro (1994) writes, the constructivist teacher must be a researcher as well, in order to understand what children are thinking about the topic at hand and how they have come to think that way. Shapiro places great emphasis on listening as both a research and teaching methodology, and she believes that successful teaching means giving great respect to the child's efforts to create understanding. Unless the teacher understands how children think about light or the water cycle, after all, she cannot help the child confront, reflect on, and rework his theories.

Driver (1995) describes what we might call the delicate dance of constructivist teaching, in which the teacher must know when to provide knowledge, when to provide experiences, and how to help the child use both to create knowledge. Like Shapiro, she argues that constructivist

teaching must begin with the child's understanding, not with a predetermined curriculum. Toward this end, Maria (1997) offers a helpful case study in which she worked with a child for nearly 2 years (from age 5 to age 7) in a study of the shape of the earth, the causes of night and day, and related concepts. While Maria's goal was to observe the formation of alternate conceptions, her study is also a nice example of the artful use of conversation. What she and Shapiro have in common is the idea that the constructivist teacher of science must understand learning as a social, emotional, and cultural experience as well as a cognitive one (Shapiro, 1994).

Chinn and Schaverien (1996) describe four types of conversations that may be used both to elicit children's ideas and to assist children in the refinement of their thinking. "Coffee-table conversations," for example, are child-directed talks in which the child presents a proposed solution to a problem, much as an architect presents building plans for review. The act of placing the drawing or other construction on the table, they found, creates some emotional and cognitive distance between the child and her work, allowing the child and teacher to engage in productive review of it. Their work is recommended as a careful analysis of the power of conversation when led by a skilled teacher.

Documentation

Our discussion of children's construction of mind raised two issues for the teacher of young children: children's ability to recognize cognitive conflict and to adopt another person's perspective well enough to exchange ideas successfully. To these, we might add a third developmental constraint: children's ability to remember. These skills develop gradually in the young child, becoming more robust over time. In the meantime, documentation of children's thinking can be an effective way to support their thinking.

Beyer (1997) describes the importance of making visible "the invisible substance of thinking." He advocates using any appropriate media—audio, video, or chalkboard—that can increase children's metacognitive reflection, or thinking about thinking. In Reggio Emilia, teachers use photographs, transcripts, audiotape, and other media to record the stages in children's thinking about a given topic. This information is not only valuable for the children, as we will discuss, but becomes an invaluable resource for the teachers, both as they plan new experiences (in Reggio, where the curriculum emerges from the work of the children, such documentation is essential) and as they share the learning process with parents, who are considered partners in the learning.

The child's construction of knowledge cannot be rushed; it requires adequate time for exploration in the environment, testing theories, and representing and discussing ideas. Extended projects that emerge from children's interests and focus their thinking on a particular topic can become powerful platforms for learning (Katz & Chard, 1996). The challenge is to help the child relate new experience with previous thinking. Four- and five-year-olds can add new meaning to a past experience but need a photograph to scaffold their memory of the past event. Photographs allow the teacher and child to discuss the past events as a narrative sequence that leads to something interesting. At the same time, when several children can look at the same series of photographs, they have a common referent for the construction of shared meaning and alternative perspectives. In addition, the very act of documenting children's thinking makes clear that their thinking is respected and valued (see, e.g., Helm, Beneke, & Steinheimer, 1998).

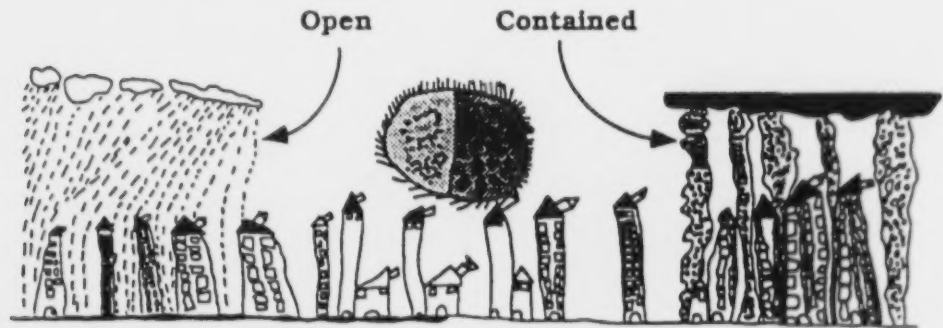
Photographs and videotape can be powerful tools that help children increase their reflective thinking and inference-making. The teacher is, in effect, modeling mnemonic strategies for the child. This practice, in turn, brings with it the responsibility that we, in some deliberate fashion, transfer these strategies to the child. One way to do this is to allow the children to gain experience with these media so they can eventually snap the photographs or zoom in with the video camera and decide which pictures or footage to capture for later review.

Drawing to Learn

There is a movement at work in education to place more emphasis on how children represent science questions. It is clear from the history of science that solutions are determined, in part, by how one represents the problem. For example, one may try to improve one's chess game by drawing a sequence of boards with all the pieces in each frame or by writing out a column of letters and numbers to represent a sequence of moves piece by piece. The drawings are more likely to elicit strategies about board development; the alphanumeric list is more likely to identify a weakness in overusing the queen or underusing pawns (see Forman, 1985).

For many years, Rosalind Driver (1989) asked science students to draw posters of their concepts, such as their naive theories about solids, liquids, and gases (see also Russell et al., 1989). From these early drawings children begin to ask wonderfully paradoxical questions: What's the stuff between the particles of matter? What holds the particles together in solids that is not there in liquids? This work has been done mostly with older children and has been used primarily to identify the children's

Figure 6.3. Simone's drawing of the rain cycle. The arrows (added to the original drawing) point to the free-fall water in the open on the left and the "pipes" for the water going up on the right.



misconceptions. By extending this work, one could understand how drawing provides a source of new knowledge, not just a record of existing knowledge.

At the University of Massachusetts we have developed a graduate seminar titled *Drawing to Learn*. The thrust of the course is to understand the mechanism by which children, in the act of drawing their theories, gain a better understanding of their misconceptions and thereby reconstruct their misconceptions into a more sensible theory. This course refers to work by Driver (1989), Larkin and Simon (1987), and others, but for the early education years, the course gives careful attention to work that is coming from the preschools in Reggio Emilia, Italy. We can consider the example of a 5½-year-old, named Simone, who drew her understanding of the rain cycle (see Figure 6.3) and described it as follows:

The rain falls on the houses, on the umbrellas and on the trees, then it goes on the earth, in the courtyards, then things dry up when it's sunny. Instead of continuing to go around the houses, the rain dries up, the sun heats the rain that has fallen and that's how it goes away afterwards, it goes back into the clouds and then it starts to rain again. (Cited in traveling exhibit, *The Hundred Languages of Children*, The Commune of Reggio Emilia, Italy)

From this description it seems that Simone has a rather complete understanding of rainfall and evaporation. But a closer look at her drawing reveals that the rain going up needs to be contained inside something like

a tube (see arrow on right of Figure 6.3). These marks suggest that she is still thinking of water as liquid, and therefore this heavier-than-air substance needs to be contained in order to be transported back into the clouds.

At this point the teacher in Reggio would intervene with a comment such as this: "These marks [the tube] are very interesting, Simone. Could you tell me why you drew them?" The drawing becomes a platform for discussion among teacher and children. Drawings are frequently shared with the group, usually about four children, and the children discuss what the drawings mean. The drawings help the children develop a common referent, and this in turn helps them reconstruct their misconceptions about a science topic (see Forman, 1989). The teachers in Reggio have also used drawing to teach other concepts, such as shadows, mirror reflections, gravity on the bottom of the earth, and algorithms for making tea.

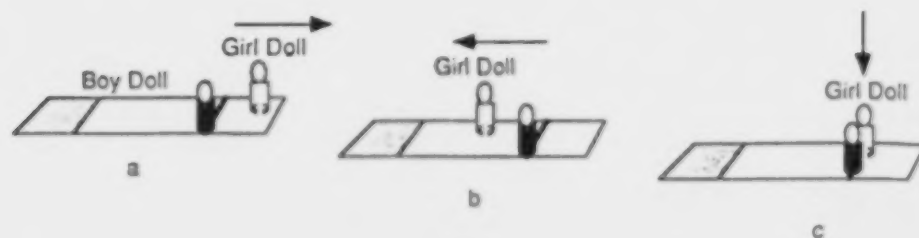
We have extended drawing to learn in the United States with other themes, such as simple machines and the crystalline growth of snow. Through careful analysis of the process of drawing, we have determined that children must make a shift from drawing how something *looks* to drawing how something *works*. This means children have to go beyond the literal stage so common around age 6 or 7, when they are overly concerned with picture realism (Gardner, 1980). Teachers and children should not confuse drawing to learn with learning to draw. These are fundamentally different enterprises.

Collaborative Problem Solving

Educators have appreciated the power of group discussion for some time, but only recently have they begun to formalize the dynamics of collaborative problem solving. Group problem-solving research has moved beyond the realm of teaching good citizenship and into mainstream cognitive science. Through a revival of interest in Vygotsky (1978) and the reconstruction of Piaget's theory of knowledge (Doise & Mugny, 1984), basic and applied research has been forthcoming on how knowledge construction is essentially a social endeavor.

Tudge and Caruso (1988) present the implications of this research base for early childhood education. In summary, they describe the type of setups that generate quality collaborative problem solving, such as balance beams and marble rollways. They then proceed to explain just what the children do in collaborative learning that deepens their understanding. This list includes the role of cognitive conflict, the need to explicate thinking for others, and the use of inferences that go beyond what can be

Figure 6.4. Representation of the debate among four children on what it means to give the girls a handicap in a long-jump contest.



seen. These processes are more probable within social debate than when a child is working alone.

We can look again at practices in Reggio Emilia, Italy, for wonderful examples of collaborative problem solving in science. In one project, four children, ages 5½ to 6, volunteered to design an athletic event, the long jump. In the course of this project they were faced with problems of many types: rules of fairness, how to measure the long jump, how to divide the school into ability flights, and how to read the symbols on a 10-meter tape (see Forman & Gandini, 1991). Of particular interest was the following episode on how (and whether) to offer girls an advantage. This episode brings into conflict two interacting variables, speed and fatigue, as well as a challenge of sexism from the girls. The episode begins as follows:

In order to focus the discussion of rules the teacher helps by asking the children to make a small replica of the track itself. This serves as a common referent from which the children can discuss rules of fair competition. The children have made the sand pit from a highly textured paper and the runway from a less textured paper. To facilitate the discussion the teacher provides the children with small wooden dolls that the children can move around to clarify something said.

A discussion ensues about the girl and boy runners. Augusto offers his opinion that girls cannot jump as far as boys. Silvia and Stephania listen, but do not agree. Silvia says, "I told you a thousand times, woman also do sports and can do things even stronger than the Long jump."

Augusto pushes his point that the girls need some sort of handicap to make the competition fair. "But, do you want more run up? Yes or no?" The girls need to start further back, so they will have more space to run before they jump. Augusto explains as he positions the girl doll further back [Figure 6.4a]. The girl doll, in the red pants, is placed several inches behind the starting line.

Stephania protests, "But if they are tired, they cannot make it, they cannot jump."

Lorenzo intervenes. He says, "Maybe I have misunderstood. She has to start further up, because she has very little strength and this way she doesn't get tired." He moves the girl doll, in red pants, in advance of the boy doll [Figure 6.4b]. Lorenzo no doubt believes that he is being fair.

Stephania takes a definite stand on this issue. "Hey no, come on. We have already decided the rule. The girls should start from the same line of departure as the boys." Silvia agrees completely with Stephania.

And with this assertion, Silvia moves the girl doll back to the start line with the boy doll [Figure 6.4c]. But for the boys the problem persists and will only be resolved toward the end of the project when they implement their rules for the actual event. (Forman & Gandini, 1991)

If we review this sequence, we can better understand the learning that takes place when children discuss issues among themselves. First, the medium of the collage layout and the dolls improve the chances that the children will share a common set of references. Young children have a tendency to use indefinite words, such as "do this" and "not that," which makes it difficult to share meanings verbally. So the tangible materials, combined with their movement and the children's gestures, make it possible for the children to focus on the debate rather than the verbal skills of making their words unambiguous.

Then, the issues themselves were wonderfully rich. Just for the moment, let's accept Augusto's premise that girls should be given an advantage. How could this be done fairly? Augusto reasons that the girls should be moved back to increase the distance from the jumping point. This is a reasonable suggestion given his premise that more distance means more speed, which in turn means longer jumps. Of course, this assumption is true only if the girls cannot reach maximum speed in the original running space. The extra running space is superfluous beyond the point of maximum speed. So, extra running space may not mean more speed.

Stephania counters Augusto with her concern about the runner getting too tired. If you move the runner back, the greater distance will make the runner more fatigued. Perhaps since this girl doll represented herself, she related more to the tired feelings than did Augusto.

But Lorenzo counters Stephania by saying the lesser distance means less fatigue, so he moves the girl doll up. Thus we see the advantage of having several children relate to the same issue. They do so in different ways, and the system of relations becomes richer for all children. More distance increases speed, which increases the jump for Augusto, but more distance increases fatigue, which decreases the jump for Stephania. Then does it follow that less distance decreases fatigue, which increases the

jump, in Lorenzo's solution? Lorenzo does not consider that the effects of speed and fatigue might cancel each other out. For children to combine two relations, they need representations more formal than wooden dolls.

The problem is simply short-circuited for the moment by Stephania, who insists that there is no reason to give girls an advantage. End of sequence, but the stage has been set for a return to this problem during the actual long-jump event. The children decide that it is all right for the jumpers to begin wherever they like. The children learn to distinguish rules of fairness from strategies of choice.

CONCLUSION

The model of science thinking in Figure 6.2 helps us develop a constructivism that accounts for the interchange among the child, her peers, and her teacher and that recognizes both developmental constraints and the importance of the child's intuitive understandings about science. This perspective leads us to a social constructionism that is child-centered while acknowledging the role of the teacher in bridging the child's discovery process and the use of socially constructed symbol systems.

The flow of thinking represented in Figure 6.1 can help us summarize what we have said so far about teaching. Teachers can enter this three-part dynamic flow in a variety of places. Class activities can be structured to increase the probability of unexpected events (*What's wrong here?*). Teachers can help children make better and better representations of what happened through drawings, diagrams, charts, lists, and observational records (*What happened here?*). Teachers can encourage children to debate and thereby reflect upon the quality of their proofs (*What's the proof here?*) and so challenge the face validity of the familiar.

Special attention should be given to the developmental level of children within each content area. Proof for young children can be a summary of the events as observed, but for older children, proofs can rely on necessary truths of deduction. For the younger child, heavy objects made of wood float; heavy objects made of metal sink. The older child will want more than an endless list of floaters and sinkers. So for older children, proof goes beyond the givens.

Scientific reasoning begins with a question. The question might be presented by the teacher, but before scientific reasoning kicks in, the children have to sense the conflict between what was expected and what was observed. We know from the diaries of Susan Isaacs, Nathan Isaacs, Jean Piaget, Frances Hawkins, and David Hawkins that children are indeed curious about a multitude of events. But these do not include all of sci-

ence. Children ask about the beginning of the universe, but not about the coexistence of a star and its light. They ask about animal growth, but not about predator-prey ecosystems. They ask "Why does it rain when the sun is out?" but not "Why are the daylight hours shortening?" Questions are themselves minitheories, and a theory means that the child already has the cognitive wherewithal to relate two or more facts. But since some questions are more complicated minitheories, children cannot grasp the question itself. These questions they do not ask.

Research in early scientific thinking can inform us about why certain questions are more complex than others. This, indirectly, helps us understand why young children ask some questions and do not ask other questions. The questions that children ask can then be organized into a flexible curriculum for early science education. Research shows that an emphasis on thinking skills has an impact on achievement (Tilgner, 1990). But the implementation of basic research into science curricula continues to be a slow process. As Tilgner (1990) points out, the resistance to teaching science in the younger years is almost as common today as it was 20 years ago. We have a clearly identified need to advocate for early science education.

This advocacy should draw on research on issues that affect children's interest in and success with science, but which space has prevented us from reviewing here: research about the role of the family in promoting science learning, for example, or about why girls continue to lose interest in science in the early grades. We are also intrigued by research about children's ideas about nature, and how exposure to the natural world affects children's thinking (Nabhan & Trimble, 1994).

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